

Review

Mobile hydraulic power supply: Liquid piston Stirling engine pump

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ABSTRACT

Conventional mobile hydraulic power supplies involve numerous kinematic connections and are limited by the efficiency, noise, and emissions of internal combustion engines. The Stirling cycle possesses numerous benefits such as the ability to operate from any heat source, quiet operation, and high theoretical efficiency. The Stirling engine has seen limited success due to poor heat transfer in the working chambers, difficulty sealing low-molecular weight gases at high pressure, and non-ideal piston displacement profiles. As a solution to these limitations, a liquid piston Stirling engine pump is proposed. The liquid pistons conform to irregular volumes, allowing increased heat transfer through geometry features on the interior of the working chambers. Creating near-isothermal operation eliminates the costly external heat exchangers and increases the engine efficiency through decreasing the engine dead space. The liquid pistons provide a positive gas seal and thermal transport to the working chambers. Controlling the flow of the liquid pistons with valves enables matching the ideal Stirling cycle and creates a direct hydraulic power supply. Using liquid hydrogen as a fuel source allows cooling the compression side of the engine before expanded the fuel into a gas and combusting it to heat the expansion side of the engine. Cooling the compression side not only increases the engine power, but also significantly increases the potential thermal efficiency of the engine. A high efficiency Stirling engine makes energy regeneration through reversing the Stirling cycle practical. When used for regeneration, the captured energy can be stored in thermal batteries, such as a molten salt. The liquid piston Stirling engine pump requires further research in numerous areas such as understanding the behavior of the liquid pistons, modeling and optimization of a full engine pump, and careful selection of materials for the extreme operating temperatures. Addressing these obtainable research quandaries will enable a transformative Stirling engine pump with the potential to excel in numerous applications.

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1. Introduction

Mobile hydraulic power supplies are a critical subsystem in numerous applications such as hydraulic hybrid vehicles, construction equipment, and agricultural equipment. The mobile hydraulic power supply for these applications typically consists of an internal combustion engine coupled with a hydraulic pump. Both the coupling of the components and the inherent limitations of the prime mover create efficiency, power density, and fuel choice limitations for this power supply. As the global community is embracing the need for efficient systems that are powered by sources other than fossil fuels, conventional mobile hydraulic power supplies will have difficulty entering into the category of “green energy”.

The first area of limitations for conventional mobile hydraulic power supplies is the coupling of the prime mover and the pump. Consider the numerous kinematic connections created when an internal combustion engine drives a hydraulic piston pump: the camshaft actuates the engine valves, the engine piston drives the connecting rod, the connecting rod drives the crankshaft, the crankshaft drives the input shaft of the pump, the input shaft of the pump rotates the cylinder block, and finally the rotating cylinder block causes the pistons in contact with the swash plate to reciprocate. Each of these kinematic connections adds complexity, cost, and results in an energy loss. Furthermore, these numerous connections create significant constraints on the packaging of mobile hydraulic power supplies.

Previous work has explored reducing the kinematic complexity of power supplies for mobile fluid power applications. Multiple researchers have explored free-piston internal combustion engine pumps that directly couple the engine piston with the pump piston [1–3]. These systems improve the packaging of the engine, yet are limited by the internal combustion engine cycle and control

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challenges with the free-piston. Other related work towards reducing the complexity of mobile hydraulic power supplies includes monopropellant driven free-piston hydraulic pumps [4].

Before further exploring the kinematic coupling of the mobile hydraulic power supply, consider the limitations of the conventional prime mover, the internal combustion engine. The two most common internal combustion engine cycles, the spark-ignition Otto cycle and the diesel cycle both rarely exceed thermal efficiencies of 35% and 40%, respectively [5]. The short combustion time of internal combustion engines inherently results in high noise levels and considerable emissions, although this later issue has seen significant attention. While both the spark-ignition and diesel engines can be powered by bio-based fuels, the majority of these fuels utilize food crops, creating additional societal issues.

An alternative prime mover is the Stirling engine. The Stirling engine is an external combustion engine with the energy conversion efficiency potential of the Carnot cycle. The Stirling cycle is a closed cycle involves four phases: isothermal expansion, isochoric displacement with cooling, isothermal compression, and isochoric displacement with heating. The heating and cooling of the fixed mass of working gas are accomplished by moving the gas between the hot and cold sections of the engine.

1.1. Benefits of Conventional Stirling Engines

The Stirling cycle engine has numerous natural benefits over other heat engines. A prime benefit of the engine stems from the external combustion, which allows continuous combustion of fuel sources. Continuous combustion allows drastic improvements in efficiency and emissions in comparison to the rapid transient combustion in internal combustion engines. Furthermore, external combustion produces little noise, allowing a Stirling engine to be used in locations that internal combustion engines cannot, such as in homes for electric power generation or propelling submarines.

The Stirling engine is extremely flexible to fuel sources. The engine can be powered by numerous traditional fuels such as gasoline, diesel, propane, natural gas, or coal. In addition, Stirling engines can use sustainable and renewable fuel sources such as ethanol, bio-diesel, wood, rice husks. Another fuel source option that will be discussed later in the paper is hydrogen, which produces only water vapor for exhaust.

While the Stirling engine has traditionally been labeled as an external combustion engine, it can run from any heat source, not necessarily requiring combustion. One promising renewable energy source for powering Stirling engines is solar energy, with demonstrated thermal to electrical conversion efficiency of 31% [6]. Other non-combustion energy sources include factory waste heat, geothermal energy, and nuclear energy. A final exciting option for powering mobile Stirling engines is a thermal battery in the form of a phase change material. A phase change material, such as a salt, could be heated to its melting point and stored in a liquid state. During the fusion of the liquid salt, a large amount of latent heat is released, creating a constant temperature thermal energy source. A prime benefit of these non-combustion options is that they result in zero emissions from the engine.

Stirling engines can generically be classified as kinematic or free-piston. Kinematic engines create shaft work through a kinematic linkage. While many small groups have been involved in kinematic Stirling engine research, most notable was the Philips Company of the Netherlands. Following two decades of research, Philips licensed their work to General Motors and Ford. Work at these two automotive companies resulted in a limited production of mobile generators and a prototype Stirling engine powered Ford Pinto, but little long-term success [7].

Free-piston Stirling engines use the dynamics of an oscillating displacer piston to create linear work output from a power piston. This style engine is often coupled with a linear alternator to form an electric generator, such as radio-isotope Stirling generators for space applications [8]. In work at NASA Lewis Research Center, a hydraulic output free-piston Stirling engine was created by coupling a linear hydraulic pumping section with an existing hermetically sealed free-piston engine [9,10].

Additional free-piston Stirling engine pump work has been performed in the area of low-power-density water pumps using a liquid piston. This style engine used the natural oscillation of water in a U-shaped tube as the gas displacer. The research foci in this area have been tuning the oscillating frequency of the fluid columns and designing the engines for operation in underdeveloped countries [11–13]. Beyond the water pumping application, little other work relating to liquid pistons can be found in the literature. A patent search does yield a few liquid piston Stirling engine concepts, yet no further development of these concepts is available [14,15]. The concepts presented in this paper extend beyond this previous work by exploiting the heat transfer and high pressure sealing aspects of the system.

1.2. Limitations of Conventional Stirling Engines

Despite research efforts, Stirling engines have suffered from a few shortcomings that have prevented greater success. First, current Stirling engines are expensive to produce, primarily due to the complex heat exchangers that are required to heat and cool the gas outside the working chambers. The need for external heat exchangers is a result of adiabatic operation in the compression and expansion chambers, reducing efficiency and power. The external heat exchangers also increase the “dead space” of the engine, defined as engine volume not displaced by the pistons. Dead space reduces the pressure fluctuation, further decreasing power and efficiency, as further discussed below.

Power output of a Stirling engine is directly proportional to the average gas pressure. Sealing low-molecular weight gases, such as hydrogen and helium at high pressure is a significant challenge. Conventional mechanical pistons in this application exhibit significant sliding friction, creating substantial energy loss [16]. This issue has been addressed in some engine designs through the use of an elastomeric rolling diaphragm seal. However, high cost and diffusion of the working gas through the diaphragm are drawbacks of this approach [17].

The displacement profile of mechanical pistons in kinematic and free-piston Stirling engines leads to additional performance limitations. The majority of current Stirling engines deviate significantly from the ideal Stirling cycle due to approximate sinusoidal piston displacement. This results in a compressed pressure vs. volume profile, limiting the potential power of the engine by not reaching the extreme corners of the ideal cycle.

2. Liquid Piston Stirling Engine Pump

As a solution to both the shortcomings of conventional Stirling engines and the extensive kinematic connections in a mobile hydraulic power supply, a liquid piston Stirling engine pump is proposed. The liquid piston Stirling engine pump, seen in Fig. 1, uses columns of liquid to directly displace the working gas. Because the liquid pistons can conform to an irregular volume, the surface area in the working chambers can be increased by adding geometry features such as a fine wire matrix. The displacement of the liquid pistons is controlled with hydraulic valves, allowing the engine cycle to closely match the ideal Stirling cycle. The output of this

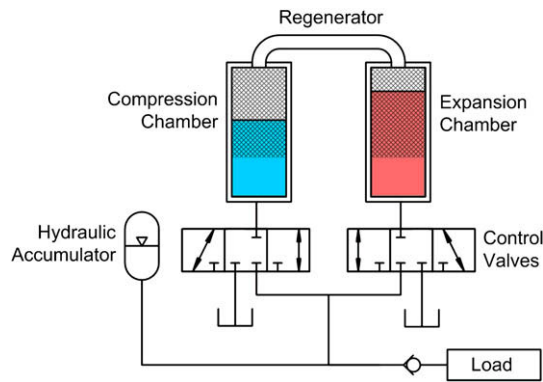


Fig. 1. Diagram of the liquid piston Stirling engine pump. The interior of the compression and expansion chambers has a high surface area porous geometry, such as a wire matrix, to improve convective heat transfer. The valves are used to control the engine cycle while the accumulator stores energy to perform the required compression work.

engine is fluid flow from the liquid pistons, creating an integral engine pump with no kinematic linkage.

The net work of the engine cycle is positive, yet work does need to be applied to the engine during the compression phase and to a lesser extent during the isochoric displacements to overcome viscous forces. During the expansion phase, a portion of the output work is stored in a hydraulic accumulator, seen to the left of the valves in Fig. 1. This stored energy is used during the phases of the engine cycle that require work input. Numerous other hydraulic circuit options exist, for example a hydraulic inertia such as a hydraulic motor connected to a flywheel, could also be used to store and release energy during the cycle.

2.1. Benefits of the Liquid Piston Stirling Engine Pump

Previous work by the author found that compressing or expanding a gas with a liquid piston approaches isothermal operation due to the large surface area in the working chambers. This previous work analytically compared a liquid piston with a mechanical piston in an industrial air compressor operating at 20 Hz. A steady-state fully developed analysis showed that using the liquid piston instead of the mechanical piston increased the convection coefficient by an order of magnitude, the surface area by nearly two orders of magnitude, and thus the heat transfer rate by three orders of magnitude for the same temperature differential [18,19]. To realize these improvements, the surface area within the working chambers is increased through geometry features such as many small diameter cylinders, a honeycomb, fins, wire matrix, or a mesh.

Improving the heat transfer in the working chambers of a Stirling engine improves both the engine power and efficiency. As presented by West, to realize efficiency improvements over conventional adiabatic operation, the heat transfer rate needs to be increased by more than an order of magnitude to overcome the transient heat transfer losses at intermediate heat transfer conditions [20]. Martini further argued that any improvement in heat transfer rate would increase the engine efficiency [21]. The multiple order of magnitude improvement in the convective heat transfer rate created by the large surface area of the geometry features in the liquid piston chamber creates near-isothermal operation, and thus significant efficiency improvements.

In a conventional Stirling engine, heat entering or leaving the working chambers must be transferred through the cylinder wall. The liquid piston also allows heat to be transferred into and out of

the working chambers through the liquid. For example, in the expansion side of the engine, the liquid can be heated in a heat exchanger. When the liquid column fills the working chamber, as occurs during every cycle of the engine, heat from the liquid is transferred to the fixed portions of the gas chamber. When the liquid piston retracts, the gas enters the space previously occupied by the liquid piston and the heat is transferred to the working gas.

Because the liquid piston enables heat transfer within the working chambers and provides thermal transport to the gas, the auxiliary gas heat exchangers found in conventional Stirling engines can be eliminated. These auxiliary heat exchangers add non-displaced volume, or dead space, to the engine, which decreases the engine power due to decreasing the compression ratio. Furthermore, experimental and analytical researches have shown that increasing the dead space, especially on the hot side of the engine, decreases the engine efficiency [16,22,23]. The complex gas heat exchangers are also a major contributor to the high cost of conventional engines. Note that the liquid heat exchangers discussed in the previous paragraph do not add dead space like the conventional gas heat exchangers as they circulate the incompressible liquid instead of the compressible working gas.

Conventional kinematic and free-piston Stirling engines are restricted to approximately sinusoidal piston displacement profiles. With this displacement profile, both the expansion and compression pistons translate sinusoidally, with the expansion piston lagging the compression piston by 1/4 of a cycle. These piston displacements result in a reduction in the area contained within the pressure vs. volume plot, as illustrated in Fig. 2. The compressed cycle area equates to a decrease in work per cycle. Actuation of the liquid pistons with valves allows direct control of the piston displacement profile, improving the power and efficiency of the engine.

Another major benefit of the liquid piston engine is the positive gas seal. Conventional mechanical piston seals create a trade-off between seal friction and gas pressure. The positive seal of the liquid piston allows the working gas pressure to be increased, further increasing engine power.

The direct hydraulic output offers an additional advantage in reducing mechanical friction. By eliminating all mechanical linkage, multiple small sources of friction are removed. Furthermore,

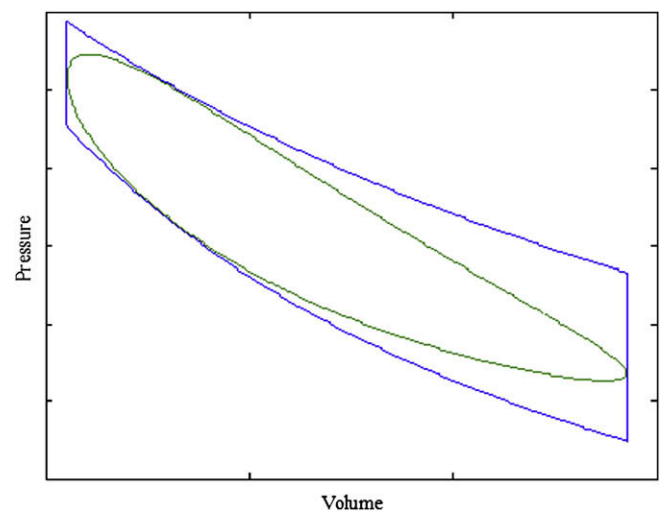


Fig. 2. Pressure vs. volume plot for the ideal and sinusoidal displacement Stirling cycles. The outer discrete segment curve is the ideal Stirling cycle while the inner continuous curve is the Stirling cycle with sinusoidal piston displacement. Note the increase in area contained within the curve for the ideal cycle, corresponding to an increase in work per cycle.

because the only moving mechanical components in the engine are the hydraulic valves, engine wear is drastically decreased. This leads to a reliable and low maintenance engine with a long operational life.

If desired, the liquid piston Stirling engine can also produce power in other domains. Shaft power can be created by coupling the hydraulic output engine to a hydraulic motor or by coupling the liquid pistons to mechanical pistons that drive a cam or a crankshaft. Through design of the cam profile, the displacement of the liquid pistons can be tuned [18]. A shaft output liquid piston Stirling engine offers an efficient, quiet, and power dense option for the replacement of internal combustion engines. Another possible output domain is as an electric generator using magnetohydrodynamics, where a conductive liquid piston converts the energy of the liquid column into an electric current in the presence of a magnetic field.

2.2. Hydrogen Powered Stirling Engine

In our increasingly emissions and global warming conscious society, the potential of using hydrogen to power vehicles is very appealing. A great deal of effort is currently being expended towards producing hydrogen efficiently and sustainably with technologies such as biological hydrogen production. To achieve adequate volumetric energy density, hydrogen must be pressurized or liquefied for mobile storage. To reach the boiling point of hydrogen, 20.3 K, significant liquefaction energy is required. When the hydrogen is converted into other forms of energy in devices such as fuel cells, this liquefaction energy is lost.

The liquid piston Stirling engine is an excellent candidate to be powered by hydrogen. As previously discussed, the Stirling engine can run from any heat source. Combusting hydrogen to heat the expansion side of the engine creates the necessary heat with only water vapor as an exhaust. Furthermore, the liquid hydrogen can first be used to cool the compression side of the engine before being expanded into a gas for combustion. Cooling the compression side of the engine to near 20 K drastically increases the power output of the engine due to the large temperature difference. Even more exciting is the potential increase in the thermal efficiency of the engine. If a Stirling engine is operated between 300 K and 800 K, the theoretical efficiency is 62%. If a Stirling engine is cooled by liquid hydrogen and operates between 20 K and 800 K, the theoretical efficiency is 98%.

2.3. Regenerative Operation

In addition to improving energy conversion efficiency, numerous applications can reduce energy consumption through energy regeneration. Because the Stirling cycle is reversible, a Stirling engine can be used as a heat pump to store thermal energy. The thermal energy can be stored at a constant temperature in a phase change material, such as a molten salt. The latent heat of possible materials range from 200 to 300 kJ/kg, providing high energy density [24]. For comparison, modern composite hydraulic accumulators have an energy density of approximately 5 kJ/kg and nickel-metal hydride batteries have an energy density of approximately 250 kJ/kg [25,26]. In a hydraulic hybrid vehicle, regenerative engine operation provides an excellent complement to a high power density hydraulic accumulator. For this type of a system, the hydraulic accumulator could supply transient high peak power requirements while the engine could generate and regenerate large quantities of energy at lower power levels.

While regenerative operation is not attractive for conventional Stirling engines due to the low thermal efficiency, the high theoretical efficiency of a liquid hydrogen powered engine makes the

concept practical. Regeneration with the Stirling engine provides an excellent alternative to storing energy in electric batteries, which poses problems due to limited operating life, cost, and environmental issues relating to their chemical composition and recycling. Energy regeneration does not need to be limited to ground transportation vehicles such as passenger cars, trucks, and trains, but is also applicable to many other applications such as earth moving equipment, mining equipment, and factory automation equipment.

2.4. Applications for LP Stirling Engine Pumps

The applications for a compact and efficient liquid piston Stirling engine pump are wide-ranging and diverse. Applications span fields including transportation, robotics, agriculture, construction, mining biomedical, power generation for both terrestrial and space applications, and many others. The flexibility of the engine to various applications is catalyzed by the ability to operate from any heat source, including renewable and sustainable options.

In the transportation field, the liquid piston Stirling engine pump is a logical choice for hydraulic hybrid passenger cars, trucks, and train locomotives. The ability to utilize any fuel source, including liquid hydrogen, or operate from a thermal battery, creates an environmental friendly transportation option. Furthermore, combining energy density thermal storage with regenerative operation is an enabling technology for hybrid vehicles of the future. Other promising transportation applications for liquid piston Stirling engines include boats, ships, and submarines.

The field of robotics is seeing strong growth in civilian, military, and educational sectors. The high power density of hydraulics combined with a compact and efficient mobile hydraulic power supply is a natural solution for numerous mobile robotic applications. The scalability of the engine enables applying this technology towards applications from small swarm robots to medium sized rescue robots used to lift large loads to military convoy robotic vehicles.

3. Research Required to Enable Technology

The liquid piston Stirling engine pump presents many exciting research challenges. The research topics include modeling the behavior of the liquid pistons, modeling the system dynamics, selection of materials, and design and optimization to maximize efficiency and power density for specific applications.

The behavior of the liquid pistons is complex and must be further understood to optimize the engine operation. cursory work has already examined the balance of the viscous frictional forces and the heat transfer issue from a steady-state fully developed pipe flow analysis and found that a realistic optimal exists for the liquid piston chambers [19]. Due to the small size of the passages in the working chamber, the flow occurs at low Reynolds numbers, where viscous forces are dominant. To improve the understanding of liquid piston chambers, this work needs to be expanded to a computational fluid dynamics model that removes the simplified steady-state fully developed assumptions.

The stability of the interface between the liquid piston and the working gas is another topic requiring attention, especially for high frequency operation. Splashing of the liquid column can result in liquid entering regenerator space or entrainment of the working gas in the liquid. Modeling and experimental work are required to determine whether the surface tension of the liquid is sufficient to maintain surface stability and how the geometry of the working chamber affects this issue. This issue can be addressed through changes in the geometry of the working chambers, adding baffles or other geometry at regenerator entrance, and the use of a liquid with low gas solubility.

A unique thermal insulation challenge is created at the interface between the liquid piston and the hydraulic fluid. As the liquid pistons are used for thermal transport to and from the working chambers, the liquid temperature of one or both pistons deviates from ambient temperature. To minimize thermal energy loss, the liquid pistons must be insulated from the hydraulic fluid. The insulating device must transmit pressure between the hydraulic fluid and the liquid piston with minimal pressure drop, while minimizing the heat transfer between the two liquids. Work within the author's research group is investigating a double layer diaphragm for this application. The double layer diaphragm uses two diaphragm layers separated by an insulating material. This insulating material can take the form of fine grains of silicate or concentric ceramic discs.

Once an understanding of the liquid piston behavior is established, a full engine model can be developed. The full engine model, synthesized by combining the liquid piston model with the engine thermodynamics, will allow a formal optimization of the efficiency and power density of the system. The prime factors affecting the efficiency and power density are the mean gas pressure, compression ratio, temperature differential, convective heat transfer rate, viscous frictional forces, and operating frequency. These variables strongly interact; for example, increasing the gas velocity through increasing the operating frequency improves the output power, yet has negative effects on the heat transfer and viscous forces. Many such relationships exist within the engine design; the model will be used to optimize their interaction for specific applications towards the design of physical prototypes.

Material selection in the area of a liquid for the liquid pistons is an important area for future work. The requirements for the liquid include: stability across the temperature range of operation, low viscosity, high thermal conductivity, low gas solubility, low toxicity, and compatibility with the other materials in the engine. The selection of liquids for both the expansion and compression piston, when operating from liquid hydrogen, is especially challenging due to operating temperature. As an example, liquid options for the expansion chamber include coolants for high temperature reactors such as synthetic organic fluids, silicone fluids, and non-toxic eutectic alloys.

Beyond selection of the operating liquid, material selection for the structural components of the engine is equally important. Factors influencing material selection include high temperature creep, hydrogen embrittlement, low temperature embrittlement, and significant thermal expansion. While the liquid piston engine pump does eliminate the majority of the moving mechanical parts from the engine, the operating conditions for the remaining components are severe.

4. Conclusion

A liquid piston Stirling engine pump provides solutions to the limitations of conventional mobile hydraulic power supplies and Stirling engines. The liquid piston allows the working chamber to be designed to maximize the heat transfer to the gas while eliminating the need for sliding gas seals. The efficiency and power density of the engine are improved through eliminating the external heat exchangers, operating near-isothermal conditions, and enabling an increase in gas pressure. The natural power output from the engine is hydraulic power, creating an engine free of moving mechanical parts beyond the valves used to directly control the piston displacement profiles.

Operating from any heat source allows options such as continuous combustion of sustainable bio-fuels, direct use of solar energy, and thermal batteries. A promising step towards a "hydrogen economy" is powering the engine with liquid hydrogen. The liquid

hydrogen can first be used to cool the compression side of the engine before being expanded into a gas and combusted to heat the hot side of the engine. This drastically improves the potential efficiency of the Stirling cycle, improves power density, and results in an exhaust containing only water vapor.

A high efficiency Stirling engine makes reversing the engine cycle into a heat pump to regenerate energy a feasible option. The thermal energy can be stored in phase change materials which absorb a significant amount of latent heat at a constant temperature. When the cycle is switched back into the engine mode, the stored potential energy in the thermal battery is used to power the load. For applications such as hydraulic hybrid vehicles, this energy storage compliments the high power density hydraulic accumulator.

To enable realization, multiple research areas need to be examined. Research topics include understanding the behavior of the liquid pistons in terms of heat transfer, viscous forces, and surface stability, optimizing the full engine dynamics to maximize efficiency and power density for specific applications, and material selection for severe operating temperatures. All of these gaps in the current research knowledge appear to be surmountable.

In summary, the liquid piston Stirling engine pump has the potential to significantly improve the efficiency and power density over existing technology. The engine offers the mechanical simplicity of minimal moving parts combined with a direct hydraulic power output and the flexibility to achieve other domains of power output. Developing this innovative engine creates a multitude of challenging, yet obtainable, research opportunities.

References

- [1] Beachley NH, Fronczak FJ. Design of a free-piston engine-pump, International off-highway and powerplant congress and exposition, SAE, Milwaukee, WI; 1992, p. 921740.
- [2] Hibi A, Ito T. Fundamental test results of a hydraulic free piston internal combustion engine. *Journal of Automobile Engineering* 2004;218(10):1149–57.
- [3] Tikkanen S, Vilenius M. Control of dual hydraulic free piston engine. *International Journal of Vehicle Autonomous Systems* 2006;4(1):3–23.
- [4] McGee TG, Raade JW, Kazerooni H. Monopropellant-driven free piston hydraulic pump for mobile robotic systems. *Journal of Dynamic Systems, Measurement and Control* 2004;126(1):75–81.
- [5] Heywood JB. *Internal combustion engine fundamentals*. New York: McGraw-Hill, Inc.; 1988.
- [6] Washom B. Parabolic dish Stirling module development and test results, Intersociety Energy Conversion Engineering Conference, American Nuclear Society, vol 3, San Francisco, CA; 1984, pp. 1686–94.
- [7] Martini WR. Whence Stirling engines, Intersociety Energy Conversion Engineering Conference, vol. 4, Los Angeles, CA; 1982, pp. 1675–180.
- [8] Schreiber JG. Developmental considerations on the free-piston Stirling Power converter for use in space, International Energy Conversion Engineering Conference, AIAA, San Diego, CA; 2006, pp. 157–83.
- [9] Schreiber JG, Geng SM. Re-1000 free-piston Stirling engine hydraulic output system description, Intersociety Energy Conversion Engineering Conference, ACS, San Diego, CA; 1986, pp. 484–49.
- [10] Schreiber JG, Geng SM. Re-1000 free-piston Stirling engine hydraulic output system description. NASA Technical Memorandum 100185, Lewis Research Center, Cleveland, OH; 1987.
- [11] De Klerk GB, Rallis CJ. A solar powered, back-to-back, liquid piston Stirling engine for water pumping. *Journal of Energy in Southern Africa* 2002;13(2):36–42.
- [12] Kluppel RP, Gurgel JM. Thermodynamic cycle of a liquid piston pump. *Renewable Energy* 1998;13(2):261–8.
- [13] West CD. *Liquid piston Stirling engines*. New York: Van Nostrand Reinhold; 1983.
- [14] Conde R, Faroughy D. Fluidic-piston engine. United States Patent 6,568,169; 2003.
- [15] Howard DL. Liquid piston heat engine. United States Patent 5,195,321; 1993.
- [16] Reader GT, Hooper C. *Stirling engines*. London: E & FN Spon; 1983.
- [17] Neelen GTM, Ortegren LGH, Kuhlmann P, Zacharias F. Stirling engines in traction applications, International Congress on Combustion Engines, A26, Stockholm, Sweden; 1971, pp. 1–42.
- [18] Van de Ven JD, Gaffuri PB, Mies BJ, Cole G. Developments towards a liquid piston Stirling engine, International Energy Conversion Engineering Conference, AIAA, Cleveland, OH; 2008.
- [19] Van de Ven JD, Li PY. Liquid piston gas compression, *Applied Energy*, in press.
- [20] West CD. *Principles and applications of Stirling engines*. New York, NY: Van Nostrand Reinhold Company Inc.; 1986.

- [21] Martini WR. Investigation of the isothermalization of the hot and cold gas spaces using numerical analysis, International Stirling Engine Conference 2, Rome; 1986, pp. 683–97.
- [22] Bauwens L. Adiabatic losses in Stirling refrigerators. *Journal of Energy Resources Technology* 1996;118(2):120–7.
- [23] Kongtragool B, Wongwises S. Thermodynamic analysis of a Stirling engine including dead volumes of hot space, cold space and regenerator. *Renewable Energy* 2006;31(3):345–59.
- [24] Clark JA. Thermal energy storage. In: Rohsenow WM, Hartnett JP, Ganic EN, editors. *Handbook of heat transfer applications*. New York: McGraw-Hill Book Company; 1985. p. 1–40.
- [25] Beachley, NH. Comparison of accumulator and flywheel energy storage for motor vehicle applications, Society of Automotive Engineers (859136); 1985.
- [26] Gifford P, Adams J, Corrigan D, Venkatesan S. Development of advanced nickel/metal hydride batteries for electric and hybrid vehicles. *Journal of Power Sources* 1999;80:157–63.